FRICTION STIR WELD TOOL AND METHOD

BACKGROUND OF THE INVENTION

1) Field of the Invention

The present invention relates to friction welding and, more specifically, to a tool and method for forming lap joints by friction stir welding.

2) Description of Related Art

Friction stir welding is a process in which a rotating tool, such as a pin or probe, is urged into and/or through a workpiece, e.g., to join multiple structural members of the workpiece in a solid state or to repair cracks in a workpiece. As shown in Figure 1, the pin **12** of the tool **10** typically extends from a shoulder **14**, which can be flat, concave, or otherwise contoured, and the shoulder **14** is urged against the structural member **20** so that the pin **12** is urged into the structural members **20, 22**. The pin **12** is then urged through the structural members **20, 22** to form a continuous weld joint **26**. For example, according to one conventional friction stir welding process for forming a lap joint **26**, a friction stir welding machine (not shown) urges the pin **12** in a direction **16** and into an interface **24** defined by the two overlapping structural members **20, 22**. The rotating tool **10** is then moved in a direction **18** along the interface **24**. The motion of the rotating tool **10** generates frictional and deformation heating, thereby forming a region of plasticized material in the structural members **20, 22**. In some cases, the tool **10** is tilted approximately 2.5° relative to the structural members **20, 22** so that the trailing edge of the shoulder **14** is thrust into the plasticized material. Upon cooling of the plasticized material, the members **20, 22** of the workpiece are joined along the weld joint **26**. Friction stir welding is further described in U.S. Patent No. 5,460,317 to Thomas et al., the entire contents of which are incorporated herein by reference.

Friction stir welding has been demonstrated to be a successful joining method for forming typical butt joints. When forming a butt joint, the pin of the tool is inserted into the workpiece to extend substantially parallel to the interface between the structural members. Thus, the pin makes contact with the workpiece throughout

the interface and mixes the material at the interface. During formation of a lap joint, however, the pin is typically inserted in a direction substantially perpendicular to the interface between the structural members. That is, as illustrated in Figure 1, the structural members **20, 22** are overlapped to form the interface **24**, and the pin **12** is inserted through the first structural member **20**, through the interface **24**, and then through at least a part of the second structural member **22**. The mixing provided by the pin **12** is often insufficient to fully disperse the material throughout the interface **24**. For example, mixing can be insufficient at the "retreating side" **34** of the weld joint **26**, i.e., the transverse side of the weld joint **26** where the tangential direction of the rotational motion of the pin **12** is opposite the direction **18** of the advancement of the pin **12** through the structural members **20, 22**. In some cases, mixing may also be insufficient at the opposite side, the "advancing side" **32** where the tangential direction of the rotational motion of the pin **12** corresponds to the direction **18** of the advancement of the pin **12**. If the interface **24** is not sufficiently mixed, oxide layers that normally exist on the overlapping, or faying, surfaces of the structural members **20, 22** can still exist in a continuous, albeit deformed, configuration after the joint **26** is formed. The oxide layer at the interface **24** of the members **20, 22** extending through the joint **26** defines a weak portion of the joint **26** that is subject to failure during use.

In addition, friction stir welding of lap joints often results in a "thinning" of one or both of the structural members **20, 22** adjacent to the weld joint **26**. Thinning generally refers to a condition in which the interface **24** between the members **20, 22** of a workpiece is deformed, i.e., either lifted or lowered toward the outer surface of a respective one of the members **20, 22**. The thickness of the respective member **20, 22**, as measured between the interface **24** and the outer surface of the member, is reduced, and the member **20, 22** is therefore subject to an increased risk of failure when stressed.

Conventional friction stir welding tools and methods have been shown to form weld joints in which the material of the workpiece is plasticized and mixed, and the resulting grain structure in the weld joint is refined. However, a need continues to exist for an improved friction stir weld tool and method for sufficiently mixing and refining the workpiece throughout a lap joint. Preferably, the tool and method should be capable of forming a lap joint, in which the joint extends substantially perpendicular through the interface.

SUMMARY OF THE INVENTION

The present invention provides a rotatable tool for friction stir welding a workpiece and an associated apparatus and method. The tool includes a first pin portion that extends from a shoulder and second pin portion that extends from the first pin portion. Advantageously, the first pin portion defines a contour surface opposite the shoulder. The contour surface, which mixes the material of the workpiece during welding, can increase the mixing of the material at the interface, thereby increasing the strength of the joint. The tool can also reduce the deformation of the interface. The workpiece can be formed of materials such as aluminum, aluminum alloys, titanium, titanium alloys, copper, copper alloys, magnesium, magnesium alloys, and ferrous alloys.

According to one embodiment of the present invention, the second pin portion extends longitudinally from the contour surface of the first pin portion and the second pin portion has a width in a transverse direction that is smaller than a width of the first pin portion. The contour surface of the first pin portion defines at least one ridge extending in a spiral configuration, e.g., in a continuous spiral configuration from the second pin portion to an outer diameter of the contour surface. The first pin portion can define a cylindrical outer surface, the contour surface can be parallel to the shoulder, and the second pin portion can be tapered in the longitudinal direction away from the contour surface. Further, the second pin portion can define at least one feature extending radially therefrom, such as a generally helical thread extending from an outer surface of the second pin portion.

According to another embodiment, the present invention provides an apparatus for forming a friction stir weld lap joint in a workpiece including first and second structural portions in a lap configuration and defining an interface therebetween. The apparatus includes a rotatable tool that has a shoulder, from which the first and second pin portions extend longitudinally. An actuator is connected to the tool and configured to rotate the tool and urge the tool in a longitudinal direction substantially perpendicular to the interface so that the shoulder is urged against the workpiece. Thus, the first pin portion pin extends at least partially through the first structural portion, and the second pin portion extends at least partially through the second structural portion. The first and second pin portions plasticize a portion of the workpiece and form a friction stir weld lap joint therein. According to one aspect, the

first pin portion defines a length in the longitudinal direction that corresponds substantially to a thickness of the first structural portion of the workpiece. Thus, when the shoulder is urged against the first structural portion, the contour surface can be disposed, e.g., within about 0.050 inch, or within about 0.030 inch, from the interface.

The present invention also provides a method for forming a friction stir weld lap joint in a workpiece. The method includes positioning at least one structural member in an overlapping configuration to define an interface between first and second structural portions, rotating the friction stir welding tool, and urging the tool in a longitudinal direction substantially perpendicular to the interface. Thus, the pin extends through the interface. In particular, the first portion of the pin extends longitudinally from the shoulder at least partially through the first structural portion, and the second portion of the pin extends longitudinally from the contour surface of the first pin portion at least partially through the second structural portion. The pin portions thereby plasticize a portion of the workpiece and form a friction stir weld joint therein. The contour surface can be urged to a position near the interface, e.g., within about 0.050 inch from the interface or within about 0.030 inch from the interface.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other advantages and features of the invention, and the manner in which the same are accomplished, will become more readily apparent upon consideration of the following detailed description of the invention taken in conjunction with the accompanying drawings, which illustrate preferred and exemplary embodiments, but which are not necessarily drawn to scale, wherein:

Figure 1 is a perspective view illustrating a conventional friction stir welding device configured to form a friction stir weld lap joint between two overlapping structural members;

Figure 2 is a side view illustrating an apparatus for friction stir welding according to one embodiment of the present invention;

Figure 3 is a bottom view illustrating the friction stir welding tool of the apparatus of Figure 2;

Figure 4 is a perspective view illustrating the friction stir welding tool of the apparatus of Figure 2;

Figure 5 is a perspective view illustrating a friction stir welding tool according to another embodiment of the present invention;

Figure 6 is a section view illustrating a friction stir weld lap joint formed between two structural members according to one embodiment of the present invention;

Figure 7 is an enlarged section view illustrating a portion of the friction stir weld lap joint of Figure 6 at the advancing side of the weld joint;

Figure 8 is an enlarged section view illustrating a portion of the friction stir weld lap joint of Figure 6 at the center side of the weld joint;

Figure 9 is an enlarged section view illustrating a portion of the friction stir weld lap joint of Figure 6 at the retreating side of the weld joint; and

Figure 10 is a section view illustrating a friction stir weld lap joint formed between two structural members according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, this invention may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

Referring now to the drawings and, in particular, to Figure 2, there is shown an apparatus **100** for friction stir welding a workpiece **150** according to one embodiment of the present invention. The term "workpiece" is not meant to be limiting, and it is understood that the workpiece **150** can include one or more structural portions, each of which can be a separate structural member **152**, **154**. The structural members **152**, **154** can be configured in various configurations. Preferably, at least two structural members **152**, **154** are positioned in an overlapping configuration to define an interface **156** therebetween that can be welded to form a lap joint. A lap weld joint generally extends at an angle relative to the interface, through one of the structural members, through the interface, and at least partially through the other structural member. For example, a lap weld joint can extend normal to outer

surfaces of the structural members and the interface between the members. Alternatively, other types of joints can similarly be formed. For example, a butt joint can be formed by abutting the edge surfaces of the structural members **152, 154** and welding through an interface of the abutting surfaces. The structural members **152, 154** can also be positioned and welded in other configurations, and any number of structural members **152, 154** can be joined by the joint. In another embodiment, the structural portions of the workpiece **150** can be part of a single structural member and the friction stir weld joint can be formed in the single member, e.g., to join overlapping portions of the member, to repair a crack, hole, or other defect therein, or to affect the material properties of the structural member.

The structural members **152, 154** can be formed of a variety of materials including, but not limited to, aluminum, aluminum alloys, titanium, titanium alloys, steel, and the like. Further, the workpiece **150** can include members of similar or dissimilar materials, for example, structural members **152, 154** formed of different alloys of a base metal, including alloys that are unweldable or uneconomical to join by conventional fusion welding techniques. Unweldable materials, when joined by conventional fusion welding techniques, produce relatively weak weld joints that tend to crack during weld solidification. Such materials include aluminum and some aluminum alloys, particularly AA series 2000 and 7000 alloys. The use of friction stir welding permits workpieces **150** formed of unweldable materials to be securely joined. Friction stir welding also can be used to securely join weldable materials to other weldable and to unweldable materials. Thus, the materials that form the workpiece **150** can be chosen from a wider variety of light weight, high strength metals and alloys, thereby facilitating reduction of the overall weight of the workpiece **150** and a structural assembly formed therefrom.

The workpiece **150** formed according to the methods of the present invention can be used in a variety of applications, including, for example, frames, panels, skins, airfoils, and the like for aeronautical and aerospace structures such as aircraft and spacecraft, for marine vehicles, automobiles, and the like, as well as for other applications outside of the transportation industry. The friction stir weld joints can be used for joining large workpieces and workpieces having curvilinear geometries. In some applications, the structural members **152, 154** are joined in geometrical configurations that make difficult, or prevent, access to the opposing sides of the

workpiece **150**. For example, the structural members **152**, **154** can be joined to form a partially or fully closed body such as a tube or an airplane wing.

As illustrated in Figure 2, the apparatus **100** includes a rotatable friction stir welding tool **110** and at least one actuator **140** for rotating the tool **110**, urging the tool **110** against the workpiece **150**, and moving the tool **110** through the workpiece **150** to form the joint extending therealong. The friction stir welding tool **110** defines a shoulder **112**, from which a first pin portion **120** extends in a longitudinal direction. The first pin portion **120** defines a contour surface **122** opposite the shoulder **112**, and a second pin portion **130** extends from the contour surface **122**. The friction stir welding tool **110** is preferably formed of a material having high strength and heat resistance. For purposes of example only and not limitation, the pin portions **120**, **130** and/or the shoulder **112** of the tool **110** can be constructed of tool steel, a molybdenum alloy, such as TZM, nickel alloys, such as Rene 41 (UNS N07041), or iron-nickel alloys.

The tool **110** can also define a shank **114** or other connection portion that can be engaged by a chuck, spindle, or other member of the actuator **140**. The actuator **140** can be any of various types of actuating devices, including electric, hydraulic, or pneumatic devices. For example, the actuator **140** can be part of a machine, such as a milling machine or a drill, that is structured for rotating and moving the friction stir welding tool **110**. The actuator **140** can be operated manually, but preferably is operated by a computer, microprocessor, microcontroller or other controller, which can be programmed to operate according to a schedule such as a schedule stored in or created by a computer software program.

The shoulder **112** is structured to be urged against the workpiece **150** so that the pin portions **120**, **130** are inserted into the workpiece **150**, e.g., into the lap interface **156** as shown in Figure 2. In other embodiments of the invention, the tool **110** can be a bobbin, i.e., a self-reacting tool that includes a second shoulder directed toward the first shoulder **112** with the pin portions **120**, **130** extending therebetween. Thus, the two shoulders can be disposed opposite the workpiece **150** and frictionally engaged to opposite surfaces of the workpiece **150** while the pin portions **120**, **130** extend through the workpiece **150**. In either case, the shoulder(s) of the tool **110** can define a surface that is generally flat, tapered, concave, convex, or otherwise shaped, e.g., to engage the workpiece **150** and prevent "plowing," in which plasticized material from the workpiece **150** is pushed radially outside the circumference of the

shoulder **112** as the tool **110** is moved along the workpiece **150**. For example, as shown in Figure 2, the shoulder **112** can be tapered so that the outer diameter of the shoulder **112** contacts the workpiece **150** and prevents plasticized material from flowing radially outward. Each shoulder **112** can also define a contour surface having one or more frictional features, e.g., raised portions or surfaces such as threads, bumps, or ribs that are structured to frictionally engage the workpiece **150**. For example, as shown in Figure 5, a spiral thread **113** can be provided on the shoulder **112** to frictionally engage the workpiece **150**.

The urging force of the shoulder **112** against the workpiece **150** can be opposed by an anvil or other support device (not shown) positioned opposite the shoulder **112** or by a second shoulder connected to the pin portions **120**, **130** and positioned opposite the workpiece **150**. Thus, the workpiece **150** can be "sandwiched" between the shoulder **112** and the additional shoulder or support device during friction stir welding. Advantageously, the shoulder **112** and the second shoulder or other support device can create a seal that prevents the plasticized material from being extruded therefrom. Thus, planar or otherwise desired contours can be formed on the opposing sides of the workpiece **150** at the weld joint. The rotating friction stir welding tool **110** can be moved through the workpiece **150** along a predetermined path to thereby form an elongate weld joint. Thus, the material of the workpiece **150** can be mixed by the pin portions **120**, **130**, and the grain size of the material can be refined, possibly improving the material properties of the material at the joint.

The pin portions **120**, **130** stir, or mix, the plasticized material of the workpiece **150** during welding. Advantageously, the surface **122** of the first pin portion **120** opposite the shoulder **112** is contoured and thus facilitates the mixing of the plasticized material. For example, as shown in Figures 3-5, the contour surface **122** can define a ridge **124** extending in a spiral configuration between the second pin portion **130** and an outer diameter of the first pin portion **120**. The ridge **124** can extend continuously or only partially between the second pin portion **130** and the outer diameter of the first pin portion **120**. Further, more than one ridge **124** can be defined on the contour surface **122**. In some embodiments, the cross-sectional shape of the ridge **124** can vary along the length of the ridge **124** so that the ridge **124** extends by varying distances from the contour surface **122** or with varying widths. In addition, the second pin portion **130** can define one or more features extending

radially therefrom. For example, the second pin portion **130** can define a helical thread **132** as shown in Figures 2, 4, and 5. In other embodiments of the present invention, the second pin portion **130** can define other features such as circumferential grooves, ridges, steps, and the like. The second pin portion **130** can also be tapered, as shown. Alternatively, the second pin portion **130** can be cylindrical or otherwise shaped.

During friction stir welding with the tool **110** of the present invention, the contour surface **122** of the first pin portion **120** can assist in plasticizing and dispersing the material of the workpiece **150**. In particular, the contour surface **122** can increase the mixing of the material at the interface **156** to improve the quality of the resulting joint. According to one embodiment of the invention, the tool **110** can be structured so that the contour surface **122** is disposed proximate to the interface **156** during welding. That is, the first pin portion **120** can have a length **L** that corresponds to a thickness **T** of the first structural member **152** so that the contour surface **122** is disposed proximate to the interface **156** when the shoulder **112** is urged against the workpiece **150**. More particularly, the first pin portion **120** can be about as long as the thickness **T** of the first structural member **152** or slightly longer or slightly shorter than the thickness **T** of the first structural member **152**. The length **L** of the first pin portion **120** is generally measured between the shoulder **112** and the contour surface **122**, including the ridge **124** as shown in Figure 2. For example, the first pin portion **120** can be within about 0.050 inch of the thickness **T** of the first structural member **152**, the first pin portion **120** being either longer or shorter than the first structural member **152**, i.e., the first pin portion **120** being longer than about 0.050 inch less than the thickness **T** of the first structural member **152** and shorter than about 0.050 inch greater than the thickness **T** of the first structural member **152**. In one embodiment of the present invention, the length of the first pin portion **120** is within about 0.030 inch of the thickness **T** of the first structural member **152**. Preferably, the first pin portion **120** is not substantially shorter or longer than the thickness **T** of the first structural member **152**, which could result in the contour surface **122** not affecting the mixing of the material at the interface **156** during formation of the joint. Thus, the contour surface **122** can enhance the mixing of the material of the workpiece **150** at the interface **156** so that the material at the interface **156** is sufficiently mixed and dispersed so that the resulting joint generally exhibits a

sufficiently refined grain structure throughout. Further, the joint can be formed without substantially lifting, lowering, or otherwise deforming the interface **156**.

For example, Figures 6-9 illustrate a friction stir weld lap joint **160** formed between two structural members **152, 154** formed of 7050 aluminum. The joint **160** shown in Figure 6 was formed with a friction stir welding tool **110** defining a first pin portion **120** having a length about 0.02 inch less than the thickness **T** of the first structural member **152** so that the contour surface **122** was configured about 0.02 inch above the interface **156** during welding. As shown in Figure 6, the interface **156** is not substantially lifted or lowered at either an advancing side **162** or retreating side **164** of the joint **160**. Further, the material at the interface **156** is well mixed, as can be better seen in the enlarged cross-sectional views provided in Figures 7-9 illustrating the advancing side **162**, a center **166**, and the retreating side **164** of the joint **160**, respectively.

Similarly, Figure 10 illustrates another friction stir weld lap joint **160** formed between two structural members **152, 154** formed of 7050 aluminum. The joint **160** shown in Figure 10 was formed with a friction stir welding tool **110** defining a first pin portion **120** having a length about 0.04 inch greater than the thickness **T** of the first structural member **152** so that the contour surface **122** was configured about 0.04 inch below the interface **156** during welding. As illustrated in Figure 10, the interface **156** is deformed only slightly at each side **162, 164** of the joint **160**, and the material at the interface **156** is well mixed.

It is appreciated that the friction stir weld tool **110** can be moved through the workpiece **150** along a path that defines the desired configuration of the friction stir weld joint **160**. The path of the tool **110** and, hence, the joint **160** can be formed in any desired configuration in the workpiece **150**. In addition, the joint **160** can extend from an edge of the workpiece **150**, i.e., by configuring the tool **110** at an edge of the workpiece **150**, rotating the tool **110**, and urging the tool **110** against and through the workpiece **150**. Thus, the shoulder **112** contacts the surface of the workpiece **150**, thereby constraining the axial movement of the plasticized material of the workpiece **150**, and the pin portions **120, 130** plasticize and mix the material of the workpiece **150**. Alternatively, the weld joint **160** can begin or end at a point inward from the edge of the workpiece **150**, e.g., by urging, or "plunging," the tool **110** into the workpiece **150** at the start of the weld joint **160**, and/or subsequently retracting the tool **110** therefrom after welding.

Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.